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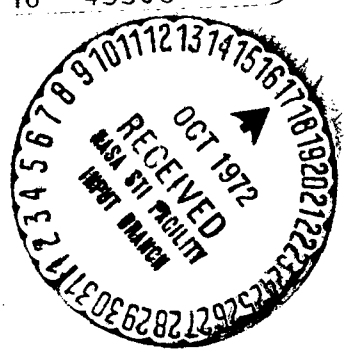

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LASERS AND THERMONUCLEAR FUSION

by

S. Witkowski*

The invention of the Q-switched laser by McClung and Hellwarth in 1962 opened new and welcome possibilities to plasma physicists for producing plasmas in temperature and density ranges not previously accessible. There now exist neodymium-doped glass lasers with pulses of several gigawatts lasting 10 to 30 ns. With the so-called mode-lock technique, it is possible to further shorten pulse duration and increase the power of picosecond pulses to more than 10^{12} W. If the radiation from giant-pulse lasers is focused with a lens on an area having a diameter on the order of 0.1 mm, radiation flux densities of up to 10^{16} W/cm^2 can be achieved. The corresponding electric field strength of the light wave is greater than 10^9 V/cm. At such high power densities, solid matter within the focal range is vaporized and ionized. In gases, an electrodeless gas discharge occurs, also called "laser spark."**

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The Laser Spark

This offers the simplest possibility for producing plasmas with lasers. When the laser is switched on, a flash of light is observed in the vicinity of the focal point of the lens, accompanied by a sharp report. Studies made in a large number of laboratories show that this phenomenon corresponds to an electrodeless gas discharge, such as produced with high-frequency coils. Its mechanism has not yet been explained in all its details. The energy of a single photon - 1.8 eV for a ruby laser - is not adequate for photoionization of the gas. It is probable that at the high power densities involved, several photons are simultaneously absorbed and that the first free electron is formed by this multiphoton-absorption process. This first electron takes up energy in the electric field of the light wave and triggers a collision-ionization avalanche, which results in the observed gas discharge. Only in extremely dilute gases, where the number of collision processes is too small, is it necessary to also assume multiphoton ionization for the formation of secondary free electrons.

Certain minimum field strengths are necessary for the occurrence of laser sparks, depending upon the type of gas, gas pressure, and the wavelength of the light; they are about 10^6 to 10^7 V/cm. The highest temperatures to date in such sparks are in the range from 10^5 to 10^6 degrees. Plasmas with considerably higher temperatures cannot be obtained by this method, since the gas discharge takes up

greater and greater volumes as laser intensity increases, and a constant quantity of plasma cannot be taken to higher temperatures, as desired. The irradiation of solids was therefore considered for the production of extremely high temperatures, around 10^8 °K, as are necessary for experiments to study thermonuclear fusion: A spherule of solid deuterium is suspended in a vacuum, irradiated with a laser, vaporized, and converted into a fully ionized plasma. The quantity of plasma produced here is determined by the size of the sphere; increased laser intensity heats this limited quantity to higher temperatures.

Irradiation of Solids

Preliminary estimates of the temperatures and densities of plasmas produced by the irradiation of solids with Q-switched lasers are provided by Basov and Krokhin [1] and by Dawson [2]. They consider a sphere of solid deuterium which is completely ionized and whose density is reduced below the cutoff density[1] for ruby laser light as the result of spherically symmetrical expansion. (It is shown that the energy requirement for ionization is small in comparison to total absorbed energy and that the ionization process can therefore already be completed during the laser pulse rise.) For the estimates, it is assumed that the entire laser radiation is absorbed in the sphere until absorption length has become greater than sphere diameter due to

[1] Cutoff density n_c refers to the electron density at which plasma frequency $\omega = (4\pi n_e e^2/m_e)^{\frac{1}{2}}$ equals the frequency of the impinging light. For ruby laser light, $n_c = 2.3 \cdot 10^{21} cm^{-3}$. At densities greater than n_c, most of the laser light is reflected by the plasma.

increasing temperature and the decrease in plasma density which results from expansion. Energy losses from radiation by the plasma can be neglected. The results of the estimates show that D_2 spherules with diameters of 60 to 600 μm can be converted completely into plasmas having average temperatures on the order of 10^7 degrees with energies of 1 to 10^3 J in laser pulses lasting from 10^{-10} to 10^{-9} s. According to these calculations, it should be possible to reach the lower boundary of the thermonuclear region with laser powers which appear to be technically possible today.

Only a few of the many experimental studies on the production of plasma by the irradiation of solids with lasers will be mentioned here. In the US, Haught, et al. [3] electrically charged spherules of solid LiH, 20 μm in diameter, and suspended it in an alternating electric field in vacuo. The spherule was irradiated with a 300 MW ruby laser and completely vaporized. The mean energy of ions in the resultant plasma was 200 eV.[2]

In the Physics Department of the Technische Hochschule München, ruby lasers were aimed at planar targets of LiD [4]. In particular, directional distribution of velocity and the quantity of plasma produced were measured here, and it was found that the resultant plasma is preferentially scattered perpendicular to the planar target

[2] In plasma physics, temperature is often characterized by thermal energy in eV; 1 eV corresponds to a temperature of 11,600 °K.

surface. In order to reconvert a portion of the kinetic energy of the expanding plasma into thermal energy, an arrangement was devised in which two plasma clouds are produced simultaneously by the laser and then collide with one another. Preliminary results indicate that the desired effect does occur. In the Soviet Union, a rather large group is working on the production of plasmas with lasers at the Lebedev Institute in Moscow. In the spring of 1968, experiments by this group were reported in which individual neutrons produced by D-D fusion reactions were observed for the first time, accompanying the irradiation of LiD targets with ultrashort laser pulses of more than 10^{12} W lasting 10^{-11}s [5]. More convincing with regard to the demonstration of fusion neutrons are experiments in the laboratory of the French Atomic Energy Commission in Limeil, the results of which were recently published [6]. In these, light from a $4 \cdot 10^{9}$ W neodymium-doped glass laser was focused on an area of solid deuterium having a diameter of 40 μm. The duration of the laser pulse was 10^{-8}s. The temperature of the resultant plasma was determined from the emitted X-radiation to be 700 eV; 500 neutrons from D-D reactions were counted per laser "shot." The results were quite reproducible. Comparative trials with targets of light hydrogen showed no neutrons.

Models for Plasma Production

Theoretical work on plasma production with lasers are for the present tied in with the estimates made by Basov and Krokhin [1] and

by Dawson [2]. They consider the laser-irradiated spherule and keep the simplifying assumption that laser energy is uniformly absorbed throughout the entire volume. The expansion of the spherule remains spherically symmetrical. The results from this theory therefore apply only to later times, following termination of the absorption process. If we wish to understand the first phases of plasma formation and its dynamics, we must take locally varying absorption and intensity of the light into consideration. Obviously, this is not simple in the case of a sphere irradiated from one direction. For this reason, Krokhin, et al [7] and Caruso, et al. [8] have based their dimensional-analysis treatment of the problem upon a 1-dimensional planar geometry. They consider the absorption of laser light in the resultant plasma and obtain the orders of magnitude of the mean values of the plasma parameters which are of interest, such as temperature, velocity, and density, making use of a number of simplifying assumptions. No predictions regarding the spatial structure of the plasma could be achieved with this method. It thus appeared desirable to more precisely study the first phases of plasma production, dimensionally reduced, using the smallest possible number of well-founded assumptions. For this reason, a unidimensional planar gas-dynamics model was developed at the Institut für Plasmaphysik. At the same time, experiments were begun which approximate the planar case as far as possible, and which were expected to check the validity of the model.

Unidimensional, Planar Gas-dynamics Model [9]

A film of solid hydrogen is irradiated from time t = 0 with constant radiation flux density Φ_o. Both the resultant plasma and the solid material are viewed as a quasi-neutral gas in local thermal equilibrium. We start with the principles of conservation of mass, momentum, and energy in differential form, taking thermal conductivity and viscosity into consideration. The degree of ionization is described by the Saha equation. The local intensity of radiation Φ (x, t) is related to incident intensity Φ_o by Beer's law:

$$\Phi(x,t) = \Phi_0 \exp\left\{-\int_x^\infty \alpha(x,t)\,dx\right\}.$$

Here, α (x, t) is the temperature- and density-dependent absorption coefficient.

The system of equations is solved numerically. The results of the calculations are shown in Fig. 1. In the upper graph is shown the density profile of the undisturbed film, 50 μm thick. At time t = 0, the laser is switched on with $\Phi_o = 10^{12}$ W/cm^2. The film is initially transparent; only a small fraction of the penetrating light is absorbed, but this is sufficient to produce enough free electrons in less than 0.1 ns that the film becomes opaque and the light is absorbed in a thin layer at its surface. This layer is strongly heated; the resultant plasma expands to the right at a high velocity. The reaction forces correspond to pressures of $3 \cdot 10^5$ atm and produce a shock wave, which passes through the film in the opposite direction. The quantity of matter

subjected to the shock wave is very much greater than the quantity which is transformed into hot plasma at the absorption front. The absorption front can therefore be considered as an almost inpenetrable ram for the shock.

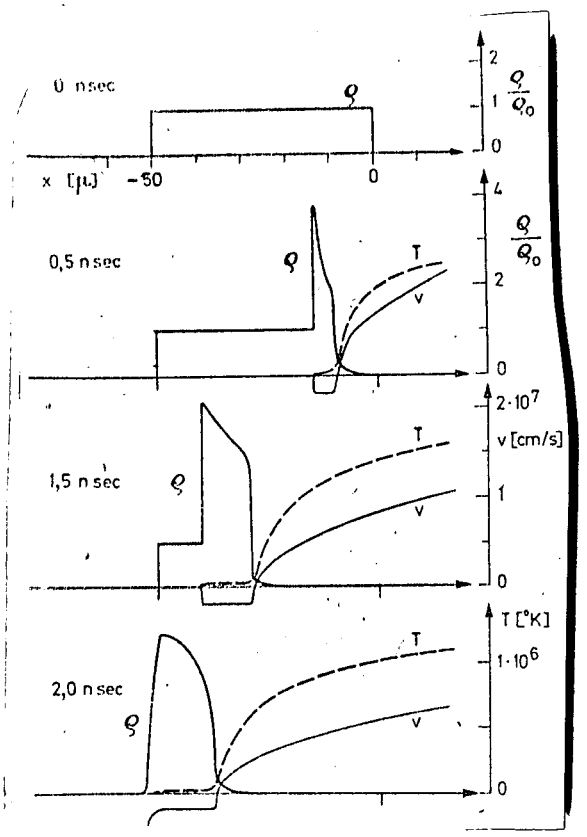

Fig. 1 - Density profile of the H film. Radiation incident from the right. $\Phi_0 = 10^{12}$ W/cm^2

Key: T: Temperature profile a: Velocity profile
(General note: Commas and numerals are equivalent to decimal points.)

The characteristics of the hot plasma, expanding toward the right, can be better seen with the scales applied in Fig. 2. Accordingly, temperatures of about $2 \cdot 10^6$ °K are reached at a distance of 1 mm from the film. Density has dropped to 10^{20} cm^{-3} at this point. More than

92% of the incident laser energy exists as thermal and kinetic energy (in about equal portions) in the hot plasma; less than 8% is transferred to the dense phase by the shock wave.

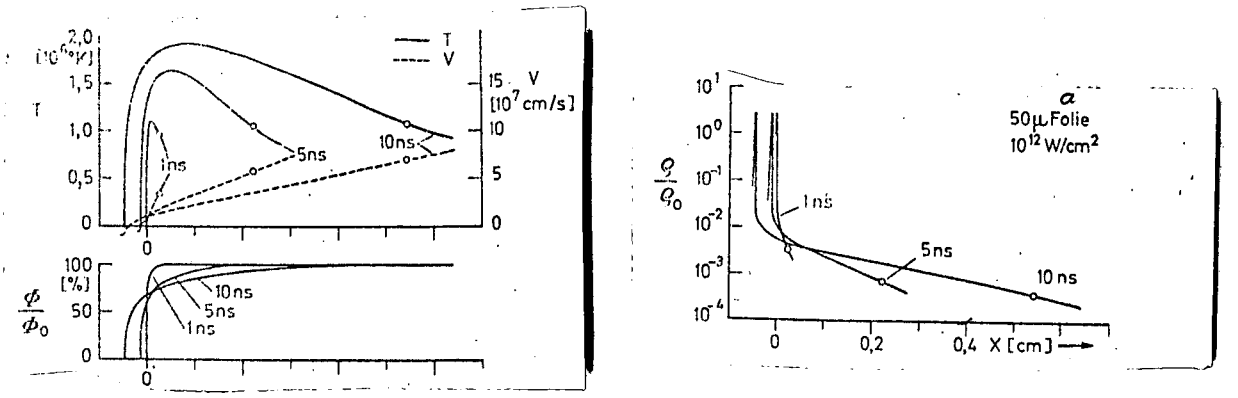

Fig. 2 - Temperature, velocity, light intensity, and density as functions of position. Radiation incident from the right.
Key: a: film

Experiments to Test the Gas-dynamics Models

Paralleling these calculations, experimental studies were made on the processes accompanying the irradiation of hydrogen films with laser light [10]. For this purpose, small discs of solid hydrogen, 50 to 1000 µm thick and 2 mm in diameter, were prepared [8] and irradiated with focused laser light. The quantity and the energy of the plasma produced were measured with ion collectors. For a radiation density of 10^{12} W/cm^2, a pulse length of 18 ns, and a focal-spot diameter of 0.14 mm, measured ion energy was 200 eV, and the total number of ions emitted within the solid angle 2π was $4 \cdot 10^{16}$.

This value for the total number of ions is in good agreement with the total number of electrons determined from interferograms which were produced holographically.

Measurements of transparency as a function of time showed that once the laser pulse begins, the film initially becomes opaque. This is in complete accordance with the Mulser model. The time which elapses until it becomes transparent again is shorter than in this model by a factor of about 20, however. The reason for this lies in the degree of deviation from planar geometry: Hot plasma is produced here only in the region covered by the small focal spot. This area acts as a punch which is driven into the film by recoil from the expanding plasma. The resultant shockwave encloses the punch in the form of a front wave (Fig. 3). The punch and front wave pass through the film with the same velocity. The major portion of matter is forced away to the sides here. The laser beam is finally able to penetrate the film unattenuated through the tunnel produced in this manner. Dark period t_D is thus determined for the most part by the velocity of the front wave, and not - as in the planar case - by the rate at which the material is converted into plasma. The velocity of the front wave (and the "punch") can be determined by measuring t_D for films of various thickness. We obtain a value of $3 \cdot 10^6$ cm/s for 10^{12} W/cm^2 in the laser focus. The degree of agreement with the shock-front velocity of $2.7 \cdot 10^6$ cm/s calculated by Mulser for the planar case is surprisingly good.

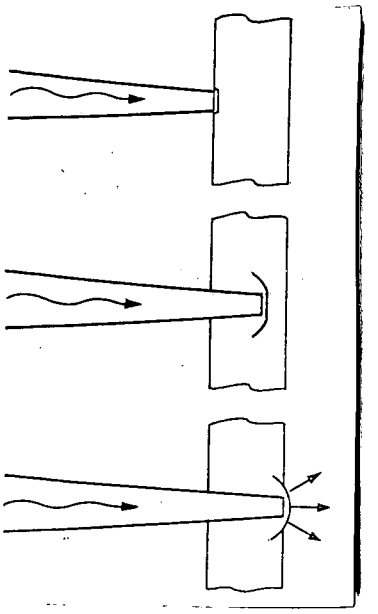

Fig. 3 - Punch (≙ laser focus) passing through the material with a front wave.

Further confirmation of the punch model is provided by image converter time-resolution photographs(Fig. 4). On the back side of the irradiated film, displacement is not observed until about 25 ns after the laser pulse has begun - upon arrival of the front wave - followed shortly by bursting of the film.

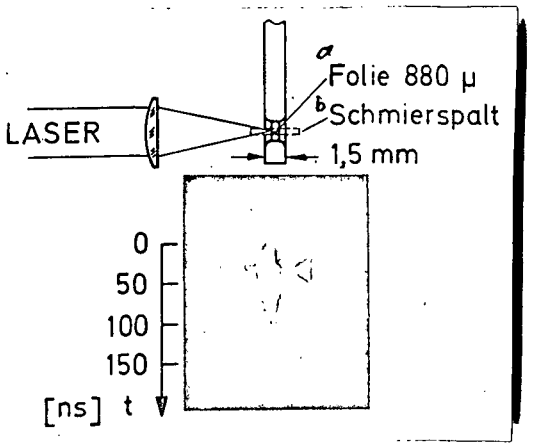

Fig. 4 - Time-resolution photograph of the penetration process. The point of the triangle marks the time at which the light succeeds in penetrating the film.

Key: a: H_2 film; b: Time-resolution slit.

The gas-dynamics model thus makes possible a valid description of all essential phenomena to be observed in the irradiation of solid hydrogen with laser light - at least in the intensity range from 10^{11} to 10^{13} W/cm^2. The formation of a strongly absorbing layer and a shock wave which moves into the solid material is characteristic. For higher intensities, it will be necessary to take the different temperatures of electrons and ions, the electric space-charge fields, laser-light reflections, light pressure, and nonlinear interactions between laser light and the resultant plasma into consideration.

Nuclear Fusion With Lasers

In the experiments at Limeil mentioned above, a deuterium plasma was produced with a 4 GW laser in which about 500 neutrons from fusion processes were observed. If we estimate the number of fusion reactions to be expected for the 4GW laser, using the gas-dynamics model, we obtain figures ranging from 500 to 10,000 reactions per laser shot, depending upon our assumptions regarding the size and shape of the plasma cloud produced. The observed number, 500 neutrons, thus appears quite reasonable within the scope of the gas-dynamics model. The problem of an energy gain from thermonuclear fusion has not been solved at all by the French experiments, however. An energy of only 10^{-9} J is released in the 1,000 fusion reactions, an infinitesimally small fraction of the laser output of about 40 J used to produce and heat the plasma. The ratio of recovered to expended energy increases with

increasing laser power. In the following, the minimum energy is to be estimated which would have to be imparted to a plasma by radiation in the most favorable case if an equal amount of fusion energy is to be recovered.

The number of fusion reactions per unit volume and unit time in a thermoplasma of infinite dimensions is

$$N_\infty = \overline{\sigma v} \cdot n_1 \cdot n_2 .$$

where $\overline{\sigma v}$ is the mean value of the product of cross section and velocity obtained with the Maxwell distribution, and n_1 and n_2 are the particle densities of the reacting components.

Mean free path λ for particle 1 before it reacts with a partner 2 is

$$\lambda = \frac{1}{n_2 \bar{\sigma}} \approx \frac{\bar{v}}{n_2 \overline{\sigma v}} .$$

This free path λ is always very much longer in the temperature range of interest to us than the mean free path l for elastic collisions

$$l = \frac{1}{n_1 \bar{\sigma}_{\text{elast}}} \approx \frac{\bar{v}}{n_2 (\overline{\sigma v})_{\text{elast}}} .$$

This means that a particle undergoes λ / l elastic collisions before it fuses with another. It will have been displaced an average distance of

$$\lambda_{\text{eff}} = \sqrt{\frac{\lambda}{l}}\, l = \sqrt{\lambda \cdot l}$$

by these λ / l collisions when it reacts with its partner. We therefore call λ_{eff} the effective free path for reactions. If λ_{eff} is

small compared to the linear dimensions R of a plasma, reaction rate is given by

$$N_\infty = \overline{\sigma v}\, n_1 \cdot n_2$$

For $\lambda_{eff} \gg R$, the reaction rate is smaller by a factor R/λ_{eff}:

$$N = N_\infty \frac{R}{\lambda_{eff}} = \overline{\sigma v}\, n_1 n_2 \frac{R}{\lambda_{eff}}.$$

These conditions exist in the case in which we are interested. In the total volume of a sphere of radius R, the energy released per unit time by fusion reactions is

$$\frac{dW_R}{dt} = \overline{\sigma v}\, n_1 n_2 \frac{R}{\lambda_{eff}} \frac{4}{3} \pi R^3 E$$

where E is energy per reaction. We now assume that at time t = 0, a sphere of radius R_o with particle densities n_1^o and n_2^o is brought to high temperature T by the absorption of laser light. An energy input of

$$W_{in} = 3\, kT (n_1^0 + n_2^0) \frac{4}{3} \pi R_0^3$$

is required for this purpose. Simultaneously, with the production of fusion energy, the sphere begins to expand. (Magnetic fields strong enough to hold the plasma together, greater than 20 MG, are not technically realizable.) For the purpose of estimation, we assume that the radius of the sphere increases with thermal velocity $\overline{v}$,

$$R = R_0 + \overline{v} \cdot t,$$

and that temperature T remains constant during this process. Total

energy released during the expansion process is then

$$W_R = \int_{t=0}^{\infty} \overline{\sigma v}\, n_1 n_2 \frac{R}{\lambda_{\text{eff}}} \frac{4}{3} \pi R^3 E \, dt.$$

How large must the initial radius R_o of the sphere be at a given density and temperature if the fusion energy released is to just equal the heating energy which is applied? From

$$W_{th} = W_R$$

using a number of transformations and integration, we obtain

$$R_o = \frac{\sqrt{2}\, 12\, kT}{(\overline{\sigma v})^{\frac{1}{2}} (\overline{\sigma v})^{\frac{1}{2}}_{\text{elast}} (Em)^{\frac{1}{2}}} \frac{1}{n_o}.$$

In this equation, $n_0 = 2\, n_1^o = 2\, n_2^o$ is total particle density, and m is the average value of the masses of the reacting components. Let us calculate the numerical value of R_o for the energetically most favorable case of a deuterium-tritium plasma with a thermoenergy of kT = 10 keV. According to [11], then $\overline{\sigma v} = 10^{-16}$ cm^3/s, E = 17.6 MeV, and $m = 4.17 \cdot 10^{-26}$ g. According to [12], $(\overline{\sigma v})_{\text{elast}} = 2.1 \cdot 10^{-13}$. Thus

$$R_o = \frac{5.7 \cdot 10^{22}}{n_o} \text{ [cm]} \quad (n_o \text{ in cm}^{-3}).$$

For a solid density of $n_o = 5 \cdot 10^{22}$ cm^{-3}, the minimum radius of the sphere is $R_o = 0.74$ cm. The required heating energy of $W_{th} = 4 \cdot 10^8$ J would have to be delivered by the laser beam within a period on the order of 10^{-8} s. Such laser outputs are greater than presently possible by a factor of 10^6 and will probably not be achieved within the next few years.

Moreover, it is doubtful whether they will ever be achieved unless totally new and different principles for the construction of lasers are discovered. In the event that a fusion reactor does produce an energy excess, it is still necessary to consider the efficiency η of the laser, which amounts to only a few percent. Thus the minimum radius of the the deuterium sphere would be still larger, by a factor of $\eta^{-\frac{1}{2}}$, and laser energy higher, by a factor of $\eta^{-\frac{3}{2}}$, than in our approximations.

Finally, we should remember that essentially only the energy balance has been used in the discussion to this point. It is still an open question as to how a sphere of radius 1 cm, containing matter having a solid-state density, can be heated uniformly to 10 keV by radiation within a brief period of less than 10^{-8} s. Whether this is even possible at all would have to be investigated by means of calculations similar to those used by Mulser [9].

Detonation of Hydrogen Bombs by Lasers

Speculations regarding the use of lasers for initiating hydrogen bombs received new impetus from the experiments at Lemeil [6]. It was explained above that laser outputs would have to be increased many orders of magnitude relative to those available today if an energy-producing fusion reactor were to be developed. The detonation of fusion bombs would require similarly high outputs and will, therefore, not be realized in the foreseeable future. Aside from this, such laser equipment would have such gigantic dimensions that it would not be transportable.

For this reason alone, it would be unsuitable for detonating hydrogen bombs.

Why the Production of Plasmas With Lasers?

Although a direct path to a fusion reactor with lasers does not appear accessible at our present level of knowledge, studies on laser-produced plasmas still yield important contributions in research on the fundamental principles of thermonuclear fusion:

1. They introduce us to a new, previously inaccessible range of temperatures and densities.

2. They permit the investigation of plasma-light interactions in ranges where nonlinear effects can occur.

3. The vaporization and ionization of small particles in vacuo, far from walls and supporting materials, allows the production of a plasma without impurities, the behavior of which can be studied in magnetic fields, and which can be further heated by other methods.

4. A laser-produced plasma could find applications as a short-period neutron source for various diagnostic purposes.

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